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FLIGHT PATH CONTROL EQUIPMENT FOR PRODUCING CURVED FLIGHT PATH PROFILES WITH MICROWAVE LANDING SYSTEMS

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16. Abstract For safety reasons, steep noise-abatement approaches must be flown along curved profiles. The characteristics of a flight path control instrument for producing curved approach profiles and guidance along these profiles are discussed in detail. The problems of flyability, accuracy, and the stability of aircraft movements are covered, and requirements to be placed on the IFR beacon system and on the flight control system are derived. Flight tests have shown that the techniques discussed contribute to a reduction in the burden on the pilot.

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Notation

DME	Distance measurement equipment, for determining slant range
ILS	Instrument landing system
MLS	Microwave landing system
TACAN	
VOR	Directional radio beacon
SETAC	Automatic landing system based on TACAN
CTOL	Conventional takeoff and landing aircraft
STOL	Short takeoff and landing aircraft
VSTOL	Vertical and short takeoff and landing aircraft
$\varkappa_L$	Beam angle of azimuth
$\varkappa_{LC}$	Commanded beam angle of azimuth
$\Delta\varkappa_L$	Azimuth deviation from commanded beam
ΔS	Horizontal displacement from commanded beam
γ_F, γ	Flight path angle
γ_L	Beam angle of elevation
γ_{LC}	Commanded beam angle of elevation
$\Delta\gamma_L$	Deviation in elevation
γ Lo	Intercept angle between flight path and runway
h	Altitude
h_c	Commanded altitude
Δh	Vertical displacement from commanded beam
D	Horizontal distance
R	Slant range of aircraft from beacon
C	Parabola constant
U	Flight path speed, aircraft speed
C_L	Lift coefficient
α	Angle of attack
S, T	Thrust
η	Elevator angle
R_s	Standard radius of curvature
ω_s	Standard angular velocity

FLIGHT PATH CONTROL EQUIPMENT FOR PRODUCING CURVED FLIGHT PATH PROFILES WITH MICROWAVE LANDING SYSTEMS

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1. Introduction

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In conventional approach and landing procedures, landing approach takes place along a straight flight path which is oriented radially with respect to the IFR beacon and lies in the direction of the landing strip. The angle of elevation of the IFR system is at the same time the commanded constant flight path angle. The commanded angle of elevation is about 3° in the conventional instrument landing system (ILS), but can be preselected by the pilot in new microwave landing systems (MLS).

Relatively steep landing approaches, with high angles of elevation, are required at airfields which are surrounded by obstacles (Fig. 2). In the case of airfields in thickly populated areas, moreover, steep approach is necessary because of the requirement that aircraft noise be kept as low as possible; for noise effects are reduced in steep approaches by the fact that the noise source is moving at a higher altitude and by the fact that powerplant thrust is markedly reduced [1-4].

The maximum steepness of the flight path is limited by the cabin inclination which is acceptable to passengers, by the maximum aerodynamic drag which can be produced, and by the required level of thrust [5]. At a low thrust level, thrust buildup is very sluggish after the fuel throttle is advanced in the case of standard jet powerplants. Thus the level of thrust must be

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* Numbers in the margin indicate pagination in the foreign text.

relatively high during a landing approach in order to be able to execute a rapid and safe missed-approach maneuver if necessary. A higher aerodynamic drag, required for a steep approach, can be generated at high speeds (U_a) with low drag coefficients (point a in Fig. 1) and at low speeds with high drag coefficients (point b). During operation at minimum drag (point c), drag is at its lowest and thus the possible flight path angle is at its flattest.

A cabin inclination which is acceptable to passengers is more /3 easily achieved during a steep approach at a low speed and the associated high angle of attack (point b) than at high speed (point a). Since a high approach speed must be reduced during a long approach procedure, moreover, a steep approach can be executed only at a particularly low speed below operation at minimum drag [6] (point b) if powerplant behavior is sluggish. In order to keep rollout length small, speed must be as low as possible during the flareout process. For reasons of flight safety, it is necessary to stay sufficiently far away from separation speed. In order to be able to execute the steepest and safest approach possible, one must keep aircraft speed, i.e. the state of aerodynamic flow, constant within narrow limits during approach, and the major element of the approach profile must be straight [5].

The high sinking speed resulting from the steep approach path is considered to be very undesirable by the pilot, particularly close to the ground, and must therefore be mitigated prior to the flareout process. The transition to a flatter, straight approach path with the conventional path angle of $\gamma = -3$ to reduce sinking speed is frequently publicized as the "two-segment approach" [1, 3, 7]. Due to the pronounced reduction in the flight path angle, the state of flight is likewise altered considerably; this results in overshoots in the flight path (Fig. 3), increased burdens on the pilot and safety problems. For reasons of flight safety, the change in flight path must be executed at relatively

high altitudes during this procedure, so a considerable portion of the possible reduction in noise is lost again. Moreover, the technical outlay for a second IFR beacon for two-segment approach is not inconsiderable.

The conventional transition from horizontal flight to steep descent results in overshooting (Fig. 3), which increases as the flight path becomes steeper. At a flight path angle of $\gamma = -6°$, for example, path angles of $\gamma = -9°$ can be produced temporarily as a result of overshooting. This conventional "intercept" method is unsuitable for steep approaches by STOL and CTOL aircraft, which can approach along steeper flight paths than usual ($\gamma = -3°$). /4

Transition problems between different guide beam segments and between horizontal flight and guide beam approach can be considerably reduced by means of nonlinear transition paths [5]. A typical steep, partially curved approach path for aerodynamic-lift aircraft is shown in Fig. 2.

Similar problems to those associated with curved elevation profiles occur in azimuth. Requirements for an increase in landing frequency through the use of separate approach paths (Fig. 4) and requirements for flying around obstacles and built-up areas sensitive to noise, e.g. schools (Fig. 5), can be satisfied by the introduction of curved azimuth profiles [8]. VSTOL aircraft require curved flight paths during transition; until now, these have not been feasible with IFR systems (Fig. 6). Rotary wing aircraft (helicopters) are best operated along approach paths which are not linear (Fig. 7).

2. Typical Characteristics of Microwave Landing Systems

New microwave landing systems (MLS) exhibit two essential advantages over the conventional instrument landing system (ILS) with regard to approach possibilities:

a. The commanded guide beam angle is optional over wide ranges in azimuth and elevation.

b. Range indication (DME = Distance Measurement Equipment) for the distance between aircraft and IFR beacon is available.

Several of the new MLSs are, in principle, purely position-finding methods which determine the location of the aircraft in terms of angle of azimuth α_L, angle of elevation γ_L and slant range R in polar or planar coordinates. In order to make these systems compatible with the ILS in terms of flight operations and indication, the position-finding signals α_L and γ_L are compared with the commanded values α_{LC} and γ_{LC}, and the deviation or error /5

$$\Delta \alpha_L = \alpha_L - \alpha_{LC} \quad (1)$$

$$\Delta \gamma_L = \gamma_L - \gamma_{LC} \quad (2)$$

is indicated on a cross-pointer instrument in the conventional manner (Fig. 8). In many MLS systems[1], the pilot is able to prespecify commanded values α_{LC} and γ_{LC}. Here, γ_{LC} is the commanded flight path angle and α_{LC} is the commanded approach direction, which can be set in the same way as in conventional VOR methods, for example.

The same problems with regard to the "intercept" method and the "cone effect" occur with this conventional signal processing as in the ILS system [10]. Curved flight paths cannot be produced in this manner.

[1] Since the SETAC system operates on the same principles, it will be called MLS, in spite of the 1 GHz carrier frequency.

3. Realization of Curved Flight Path Profiles

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The relationship between flight path parameters (altitude h, flight path angle γ_F and horizontal distance D to the beacon) and IFR parameters (angle of elevation γ_L and slant range R to the beacon) is shown in Fig. 11[2]. For a point P(D,h) or P(R,γ_L) along an arbitrary flight path, we have

$$h = R \sin\gamma_L \tag{3}$$

$$h = D \operatorname{tg}\gamma_L \tag{4}$$

Flight path angle γ_F at point P is defined as the slope of the flight path

$$\operatorname{tg}\gamma_F = \frac{dh}{dD} \tag{5}$$

The following relation between slant range R and horizontal distance D is obtained from the beacon angle of elevation associated with point P:

$$D = R \cos\gamma_L \tag{6}$$

The flight path angles which occur even in the case of extremely steep approach paths of aerodynamically supported aircraft can be considered small with respect to trigonometric functions, so the following approximations are sufficiently accurate for equations (3) through (6):

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[2] Since the characteristics of flight paths are formally equivalent in terms of azimuth and elevation, only the relations for elevation will be derived. Altitude h and lateral distance S are formally interchangeable, as are angle of elevation γ_L and angle of azimuth χ_L.

$$h \approx R\gamma_L \qquad (3a)$$

$$D \approx R \qquad (6a)$$

$$\gamma_F \approx \frac{dh}{dD} \approx \frac{dh}{dR} \qquad (5a)$$

The altitude h of the aircraft can be easily obtained from (3a) by multiplying the angle of elevation signal γ_L by DME signal R (Fig. 9). A commanded value h_c for a flight path which is fixed in space is determined by the relation between commanded altitude h_c and slant range R as shown in Fig. 11:

$$h_c = f(R) \qquad (7)$$

The commanded flight path can be produced in a function generator which is controlled by the DME signal. The schematic of a technical embodiment for curved flight path elevation profiles is shown in Fig. 10. The aircraft's altitude h is obtained by multiplying γ_L and R and is compared with commanded altitude h_c, which is determined from slant range R via a function generator. Error Δh can be indicated to the pilot, e.g. on a cross-pointer instrument, or fed into a flight control system in order to adjust it to zero. Any flight path profiles[3] can be produced and also flown by means of this method [8], which in principle is very simple, provided the aircraft, the pilot or the flight control system is capable of such.

A flyable noise-abatement approach profile for aerodynamically /8 supported aircraft will be used as an example to show how the function generator is also feasible in an analog version. As covered in greater detail in Section 1, the major element of a

[3] Two-segment profiles can also be produced with an IFR beacon for comparative studies.

steep noise-abatement approach profile is linear. The transition from horizontal flight to the steep approach leg and then from the steep approach leg to the flatter final approach leg must consist of curved flight path elements (Fig. 12). Parabolic arcs are particularly suitable as transition paths, since they can be easily realized in the function generator (Fig. 9) and permit relatively short transition paths with little discomfort to passengers [8]. Vertical acceleration along a parabolic flight path is constant. For reasons of passenger comfort and piloting accuracy, the individual elements of the commanded flight path profile must merge without abrupt changes (Fig. 12). To increase touchdown accuracy, the parabola close to the ground (Fig. 12) intersects the landing strip at an angle γ_{Lo} at the location of the IFR beacon [8]. The reduction in sinking speed along the parabola close to the ground, down to an altitude of about 15 m, can be designated as guided flareout, in contrast to actual flareout, which begins at an altitude of 15 m above the landing strip and is executed in the conventional manner without IFR guidance in elevation. A functional relationship between flight path angle γ_F and beacon angle of elevation γ_L is required to establish a suitable function generator; it is obtained by the total differentiation of (3) or (3a) [8]:

$$\gamma_F = \frac{dh}{dR} = \gamma_L + R\frac{d\gamma_L}{dR} \tag{8}$$

For $d\gamma_L/dR = 0$, we obtain a linear flight path $\gamma_F = \gamma_L$ and for $d\gamma_L/dR = C$, we obtain the desired parabola, as can be easily shown by substituting (9) into (3a):

$$h_c = R\,\gamma_{LC} \tag{3a}$$

$$\gamma_{LC} = \gamma_{Lo} + R\frac{d\gamma_L}{dR} = \gamma_{Lo} + CR \tag{9}$$

$$h_c = R(\gamma_{Lo} + CR) = R\gamma_{Lo} + CR^2 \tag{10}$$

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The flight path profile can be produced and deviations from this profile determined by two different methods.

In the first method, commanded flight path h_c is obtained with a function generator according to (10) and compared with actual altitude h (Fig. 9). Flight path deviation Δh is displayed on the cross-pointer instrument.

In the second method, the flight path is not obtained via commanded altitude h_c, but via commanded beacon angle γ_{LC}. For this reason, a comparison must first be made between γ_L and γ_{LC}, followed by multiplication by slant range R in order to determine flight path deviation Δh (Fig. 10). The function generator for generating the commanded beacon angle consists of three linear elements (Fig. 13) in accordance with equation (9) in order to produce a profile corresponding to Fig. 12. A function generator corresponding to Fig. 13 can be realized even by simple analog means. A detailed description of function generators for producing nonlinear profiles can be found in [8, 9].

4. Sensitivity of Indication

4.1. Cone Effect

In conventional IFR approaches and approaches with directional radio beacons, deviations from the commanded flight path are determined as angular errors in azimuth ($\Delta \alpha_L$) and elevation ($\Delta\gamma_L$) and are indicated on the cross-pointer instrument. Because of the lines of equal angular error passing radially through the location of the IFR beacon, this characteristic is called the "cone effect." The associated horizontal (ΔS) or vertical (Δh) deviation from the commanded flight path increases with increasing range from the IFR beacon: /10

$$\Delta h = R \cdot \Delta\gamma_L \qquad (11)$$

The pilot is only conditionally able to correct deviations in beacon angle. He primarily affects horizontal and vertical deviation (ΔS, Δh) from the commanded flight path. At a constant horizontal or vertical deviation on the part of the aircraft from the commanded flight path, a hyperbolically increasing deviation signal occurs as the beacon is approached:

$$\Delta\gamma_L = \frac{\Delta h}{R} \qquad (11a)$$

Both for a pilot and for a flight control system, this means a continual increase in the sensitivity or degree of amplification in the controlled system, resulting in unstable aircraft movements. For an indicating sensitivity of $\Delta\chi_L = \pm 2.5°$ angular deviation for full-scale cross-pointer deflection, instability occurs within a range interval of about $2000\ m < R < 5000\ m$ from the beacon for conventional transport aircraft and medium gustiness under IFR conditions (Fig. 14). When visibility is good, a trained pilot flying with a high level of concentration can reduce this range by a factor of five. From equation (11),

$$\Delta S = \Delta\chi_L R \qquad (11b)$$

the limit of stability is found at an indicating sensitivity of $\Delta S \approx \pm 100$ m [10].

4.2. Constant Indicating Sensitivity /11

The method described in Section 3 for producing curved approach profiles results, in contrast to the "cone effect," in a constant sensitivity with respect to flight path deviations, and thus in elimination of the "cone effect" [10]. In place of angular deviations ($\Delta\chi_L$, $\Delta\gamma_L$), the azimuthal (ΔS) and vertical (Δh) flight path deviations are indicated on the cross-pointer

instrument or fed into a flight control system. This method produces very good results in automatic IFR approaches, both with linear and with curved profiles, and eliminates the need for adaptation programs for reducing variation in sensitivity, required in the case of the "cone effect."

4.3. Variable Indicating Sensitivity

A constant indicating sensitivity over the entire approach range makes capture in the IFR system difficult, due to the high sensitivity required at the touchdown point. In addition, unnecessarily precise maintenance of the flight path prescribed by the beacon, necessary only close to the touchdown point, is required of the pilot at a larger distance from the latter. It is necessary to adapt indicating sensitivity to IFR beacon distance, and it appears desirable to break this down into three sections. Close to the IFR beacon, the linear deviation from the commanded flight path would be indicated on the cross-pointer instrument (Fig. 15a). At medium distances from the beacon, indication of the deviation in beacon angle has proven itself quite well (cone effect) (Fig. 15b). At larger distances from the beacon, where IFR capture occurs, indication of the linear deviation (Fig. 15c) is again desirable, but with considerably lower sensitivity than in the section close /12 to the beacon (Fig. 15a). The lines of equal sensitivity or equal cross-pointer deflection exhibit a bottle-shaped contour as shown in Figs. 15 and 16; this will be called the "bottle effect" in contrast to the "cone effect."

The constant sensitivity during the portion close to the airfield (Fig. 15a) is to be selected in such a manner that instability in aircraft motion still does not occur [10]. The limit of stability is known from conventional IFR approaches based on the "cone effect" (Section 4.1) and is found at an azimuthal indicating sensitivity of about $\Delta S = \pm 100$ m for full-scale cross-pointer deflection [10].

Sensitivity in the capture region (Fig. 15c) is to be selected so that the pilot can reach and maintain the commanded flight path with standard procedures without substantial corrective measures. The standardization of capture and thus a considerable reduction in the burden on the pilot is achieved if he is shown when standard curves for which ω_s = 180°/min must be initiated in order to enter the commanded flight path. When standard curves are flown, any flight path speed U is associated with a corresponding radius of curvature

$$R_s = \frac{U}{\omega_s} \qquad (12)$$

If indicating sensitivity in the capture region (Fig. 15c) is adjusted so that full-scale deflection on the cross-pointer instrument corresponds to standard radius R_s (Fig. 16), the pilot can then initiate the standard curve during an approach perpendicular to the commanded flight path when the pointer on the cross-pointer instrument reaches the outer boundary mark, e.g. the 3/3 mark in Fig. 16. The commanded IFR beam is reached at the proper position 30 sec later, and the curve is terminated. In an approach at 45° relative to the direction of the runway, the standard curve must be initiated approximately as the 1/3 indicator mark is reached and terminated again 15 sec later [10]. /13

Since flight path speed is approximately constant for each type of aircraft during the approach procedure, cross-pointer sensitivity in the beam entry area must be set only once for each type of aircraft.

Standard radii of curvature of up to R_s = 3000 m can be expected in landing approach. Capture in the beam takes place at ranges of R > 11,000 m (6 nm) from the IFR beacon, resulting in a maximum azimuth deviation of

$$\alpha_{Lmax} = R_s/R = 0.27, \text{ corresponding to } 15.5°. \qquad (13)$$

It follows from this that indicating sensitivity must be adjusted to maximum values of $\Delta\alpha_L = \pm 15°$ for full-scale cross-pointer deflection in the middle approach region (Fig. 15b).

Flight tests with an aircraft of the Dornier Skyservant type have shown in approaches to TACAN stations that considerable improvements in capture and beam behavior relative to the "cone effect" are achieved by varying indicating sensitivity to produce the bottle effect (Fig. 16). Flyovers may be made over the TACAN station without stability problems. The set indicating sensitivities in the three subregions shown in Fig. 15 were

a) 100 m for full-scale cross-pointer deflection
b) 10° for full-scale cross-pointer deflection
c) 1100 m for full-scale cross-pointer deflection.

Future flight tests with faster-flying aircraft will have to show whether greater azimuth deviations in the middle section, e.g.15°, are reasonable.

On the basis of the properties of curved approach profiles discussed in Section 3, a sensitivity breakdown corresonding to the bottle effect is applicable to and desirable for not only linear but also curved flight path profiles in manual and automatic approaches [10]. /14

5. Effect of Signal Quality on Guidance

The following precisions on the part of microwave landing systems are to be expected on the basis of RTCA requirements [11]:

Range	$\Delta R = 10$ m
Azimuth	$\Delta \alpha_L = 0.07°$
Elevation	$\Delta \gamma_L = 0.1°$.

The flight path error Δh to be expected from these beam errors is

$$\Delta h = \gamma_{LC} \Delta R + R \Delta \gamma_L \tag{14}$$

for elevation, where γ_{LC} is commanded beacon angle. The lines of equal flight path error Δh are plotted in Fig. 17 as a function of range and beacon angle. Flight path error increases with increasing beacon angle and increasing range. For example, a flight path error of $\Delta h = 2$ m is obtained for an angle of elevation of $\gamma_{LC} = 6°$ and a range of $R = 0.5$ km from the elevation beacon.

For conventional aircraft, which require only relatively small angles of elevation even for steep approaches, angular errors in azimuth and elevation prove to be particularly limiting in terms of flight path accuracy. In the case of VTOL aircraft and helicopters, on the other hand, distance errors can be relatively high for precision landings.

Stochastic (time- or distance-dependent) errors prove to be more critical than the stationary errors described, since accurately functioning flight control systems follow each error, which is processed improperly by the control unit as if it were a commanded flight path change. An unsteady flight and an impairment of passenger comfort result from this at conventional approach speeds. Flight path perturbations in the frequency range between the aircraft's two natural modes of oscillation -- phugoid and rapid angle-of-attack oscillation -- prove to be particularly unpleasant with regard to guidance accuracy and passenger comfort. For transport aircraft with approach speeds between 80 and 160 kn, /15

this frequency range lies between 0.015 and 0.15 Hz, and the corresponding wavelengths lie between 250 and 5000 m. High-frequency flight path perturbations with frequencies greater than 1 Hz have no effect on flight path motion, however.

In almost all cases, the quantities $\dot{h}$ and $\dot{S}$ are required for damping flight path oscillations. Approach speed $\dot{R}$ is necessary if a prespecified ground or flight path speed is supposed to be achieved under the influence of strong wind. Particularly in the case of STOL aircraft at low approach speed, wind effects can cause serious landing time changes that make a dense stacking of several aircraft impossible. Path speeds $\dot{h}$, $\dot{S}$, and $\dot{R}$ should be capable of being obtained approximately from the beacon signals without relatively long delays by differentiation.

Due to the demand for passenger comfort and for differentiability of the beacon signals, as smooth a beacon signal as possible, with little roughness must be required from the standpoint of guidance. Smoothing of the noisy beacon signal by means of low-pass filters is a poor solution from the standpoint of flight control, since a low-pass filter causes phase shifts and thus stability problems. Studies performed on two control systems for STOL aircraft [5] have shown that the delay time constant of the overall IFR system should not exceed a value of 0.3 to 0.4 sec. /16
Greater time constants result in a considerable impairment of path control characteristics. For digital MLS systems, this means that scanning frequency for data transmission should not be less than 10 Hz. A very noisy beacon signal is perhaps unpleasant, but an excessive delay time can result in problems.

One possibility for executing precision automatic approaches with very noisy beacon signals, such as in the case of TACAN, is to apply the bottle effect much as in the case of manual approaches (see Section 4). In this way, the degree of control amplification

and thus the effect of signal noise can be reduced at relatively long distances from the beacon. As the touchdown point is approached more closely, piloting precision is increased again without the appearance of stability problems as in the case of the "cone effect." The effect of signal noise (Fig. 17) is smaller close to the beacon.

6. Simulation and Flight Test Results

Curved approach profiles can be produced with variable azimuth and elevation sensitivity with the GCU 70 flight path control unit, which was developed at Bodenseewerk. This makes flight control along approach paths with three-dimensional curvature possible.

The characteristics of the bottle effect were studied at constant altitude for linear approaches to TACAN stations. It was possible to demonstrate that intercept is considerably simplified and can be executed precisely even with a side wind. Variable indicating sensitivity (bottle effect) was found to be very pleasant by the pilot, even without adaptation time. The flight path oscillations which normally occur close to the beacon (cone effect) were completely suppressed while flying over the TACAN station.

Linear approaches with flight path angles of up to -6° were executed with a Dornier Skyservant equipped with a Bodenseewerk FRG 12 flight control unit and a newly developed flareout and landing control unit, using the SETAC landing system. The landing approaches were fully automatic, including flareout and rollout down to speeds of 25 kn and corresponded to the CAT III A operating phase.

Preliminary studies on flight control with curved, steep approach profiles have shown, for the Dornier Skyservant type of

aircraft, that a pilot is capable of executing flight control along curved flight paths only with a great deal of vigilance, moderate flight path curvatures, good visibility and limited gustiness. The curved flight paths which were studied were not run in an IFR beam and were produced by prescribing sinking speeds. The tests showed that the burden on the pilot was increased primarily by the continuous change in elevator and thrust during highly curved flight path profiles in flight at high lift values, by the reduced control-surface efficiency, speed instability and the weak damping of tumbling to such an extent that a safe manual landing was not ensured under poor visibility conditions or in strong gusts or a wind differential. Similar results are to be expected for other types of aircraft.

In order to achieve exact control of the flight path and state of aerodynamic flow in steep, curved approaches, the FRG 70 integrated flight control system was developed by Bodenseewerk and tested for about 1000 flying hours. To date, more than 500 completely automatic landings have been made, including approach, flareout and automatic touchdown corresponding to CAT III A. Beacon angles of up to $\gamma_L = 6.5°$ were flown with the DFVLR's variable ILS beacon in Oberpfaffenhofen and ended with automatic landings. Flight tests with automatic approaches on curved flight paths are to be conducted with the SETAC system in Friedrichshafen /18 during 1973. Simulations of curved, steep approaches (Fig. 18) have indicated that the flight paths produced by the GCU 70 flight path control unit are maintained with a precision of 3 m during approach and 1 m during flareout and that speed errors are less than 0.8 kn in medium gustiness and a wind differential of 7 kn/ /100 ft. Such precision can be achieved neither manually nor with conventional flight control instruments consisting of stabilizer, autopilot and thrust control.

The microwave landing systems, the GCU 70 flight path control unit and the FRG 70 integrated flight control system, satisfy

the conditions required for new noise-abatement approach techniques. However, information is lacking on the flight paths which are required from the standpoint of flight operations and safety. For reasons of flight safety, standard procedures will probably have to be chosen from the large number of possible flight paths.

7. Summary /19

Microwave landing systems facilitate orientation in the approach area of an airport. Approach profiles which are curved in azimuth and elevation can be produced with easily developed flight path control instruments, making operation along three-dimensionally curved flight paths possible. Aircraft noise can be considerably reduced by means of these flight paths.

In order to improve manual and automatic operation along curved flight path profiles, it is necessary to vary measurement sensitivity for flight path deviations as a function of distance from the IFR beacon. Variation of measurement and indicating sensitivity (bottle effect) suppresses the unpleasant "cone effect," makes a simple, accurate and standardized intercept procedure possible, and permits accurate piloting before and during the flareout phase. The unstable motions which occur close to the transmitter with the "cone effect" are eliminated.

The increase in flight path control accuracy is accompanied by more stringent requirements to be placed on the signal quality of IFR beacon systems. A low noise level and the short delay time in the generation and transmission of IFR signals are particularly important.

With the GCU 70 flight path control unit, curved flight paths can be produced with variable measurement and indicating sensitivity with respect to azimuth and elevation. An integrated flight control

system is necessary for accurately maintaining these flight paths, since the pilot is overtaxed by the continuous readjustment of control surfaces and thrust.

The new microwave landing systems, the GCU 70 flight path control unit and the FRG 70 integrated flight control system, satisfy the conditions required for new approach techniques.

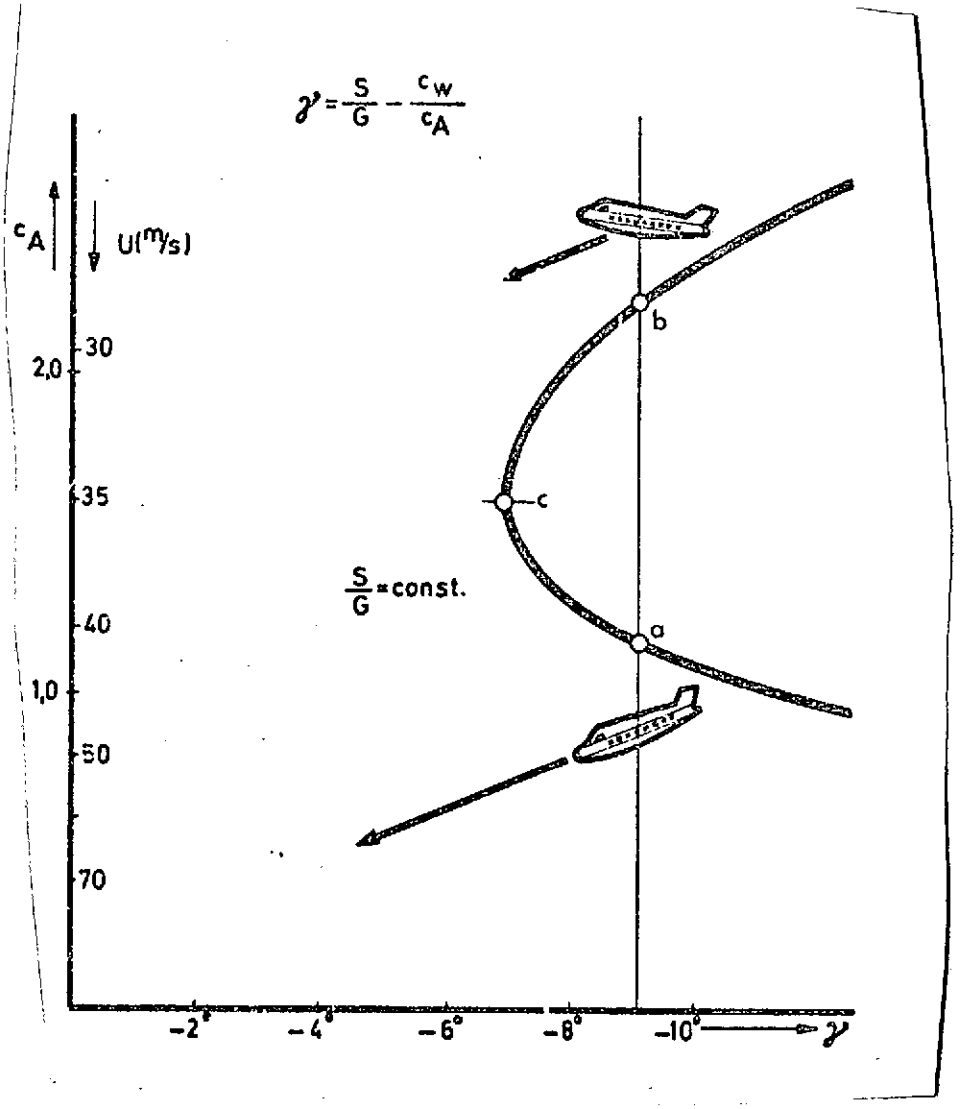

Fig. 1. Flight path polar curve.

Key: S = thrust
B = aircraft gross weight
c_W = drag coefficient
c_A = lift coefficient

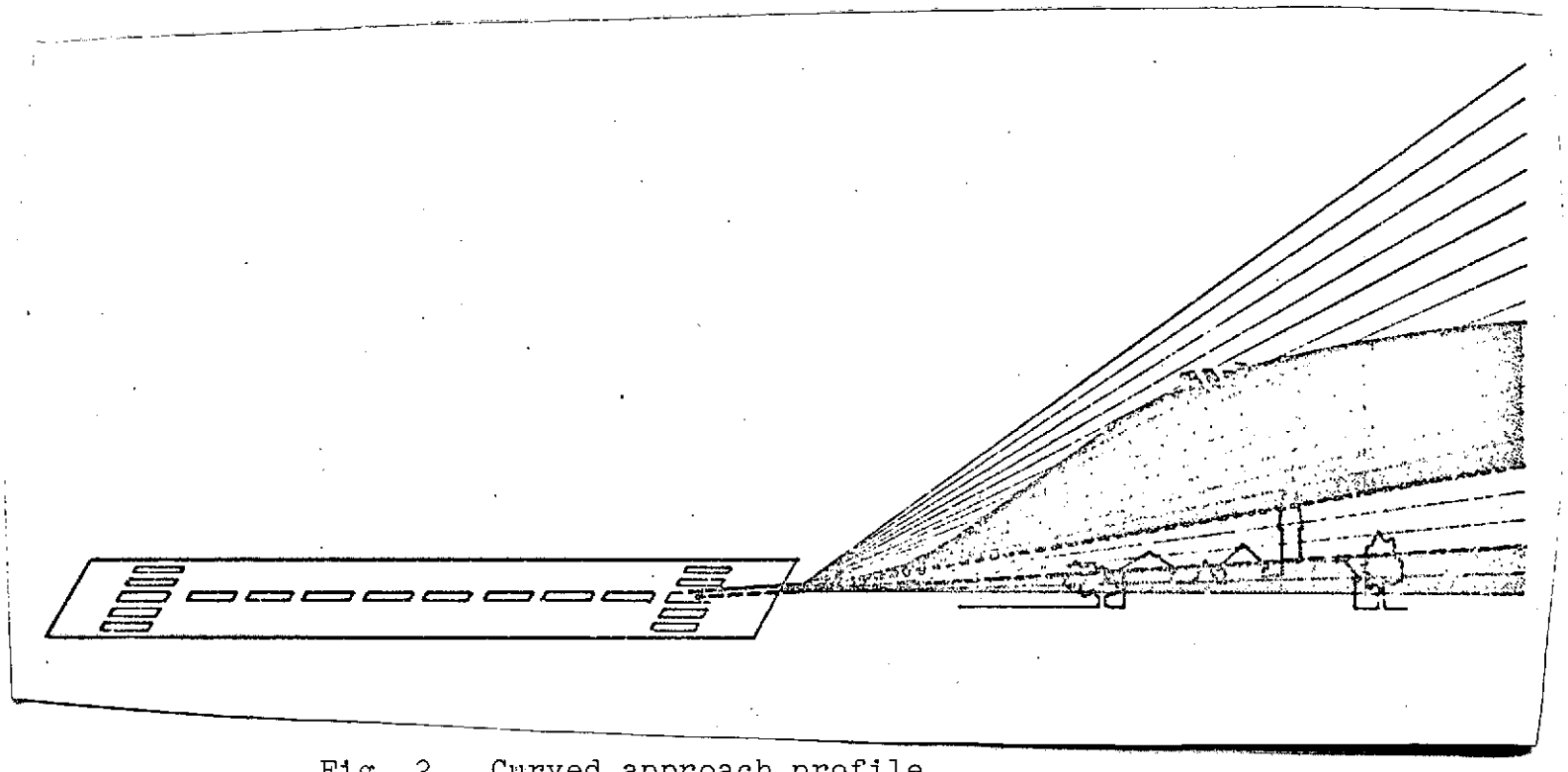

Fig. 2. Curved approach profile.

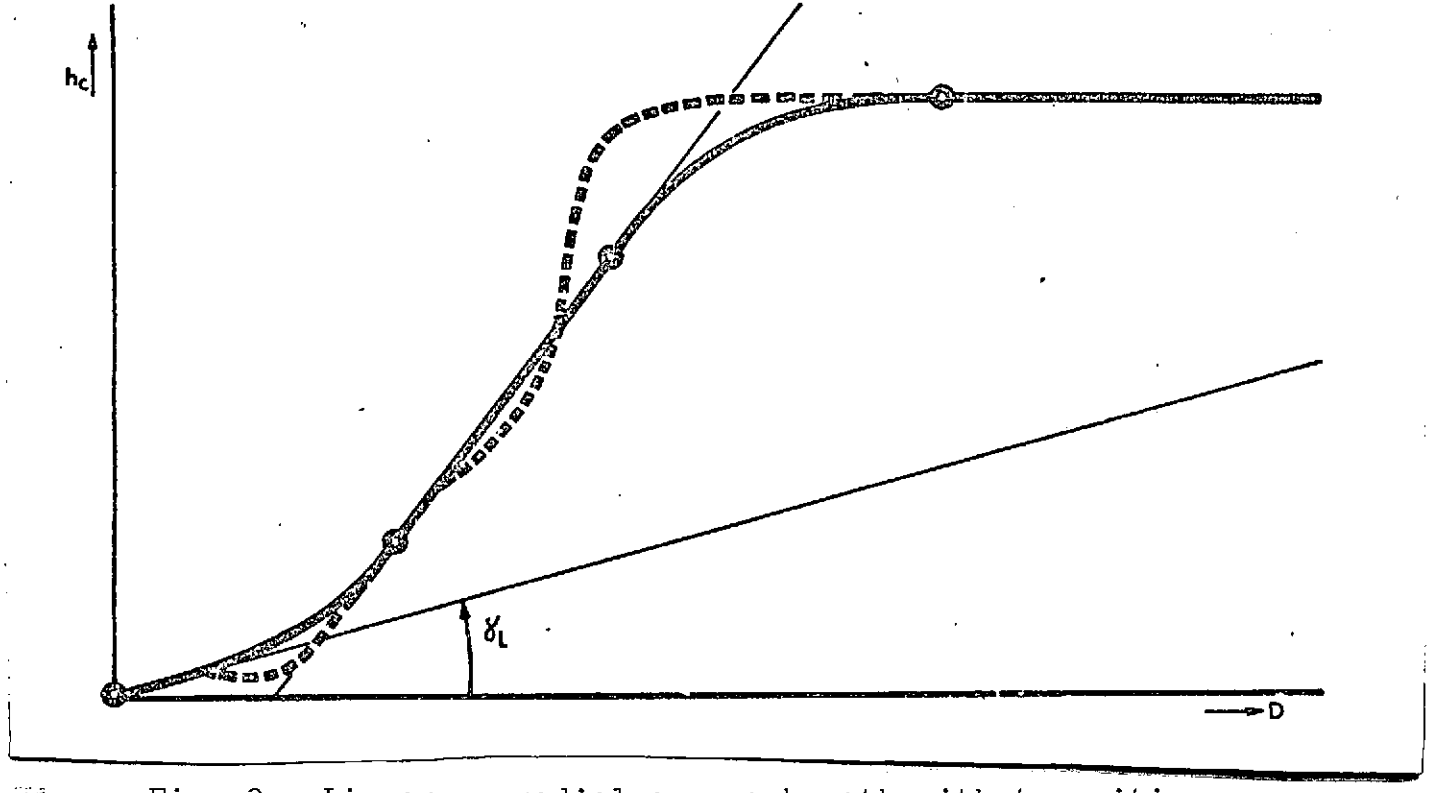

Fig. 3. Linear nonradial approach path with transition parabolas.

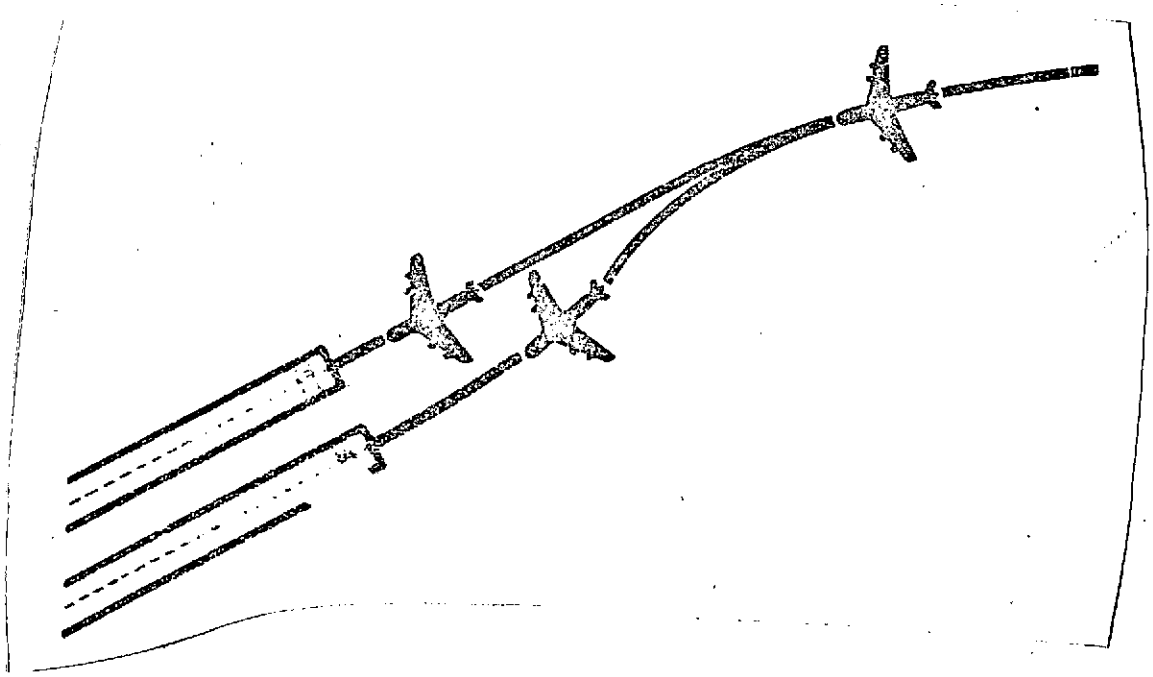

Fig. 4. Curved azimuthal path (from D. R. Clifford).

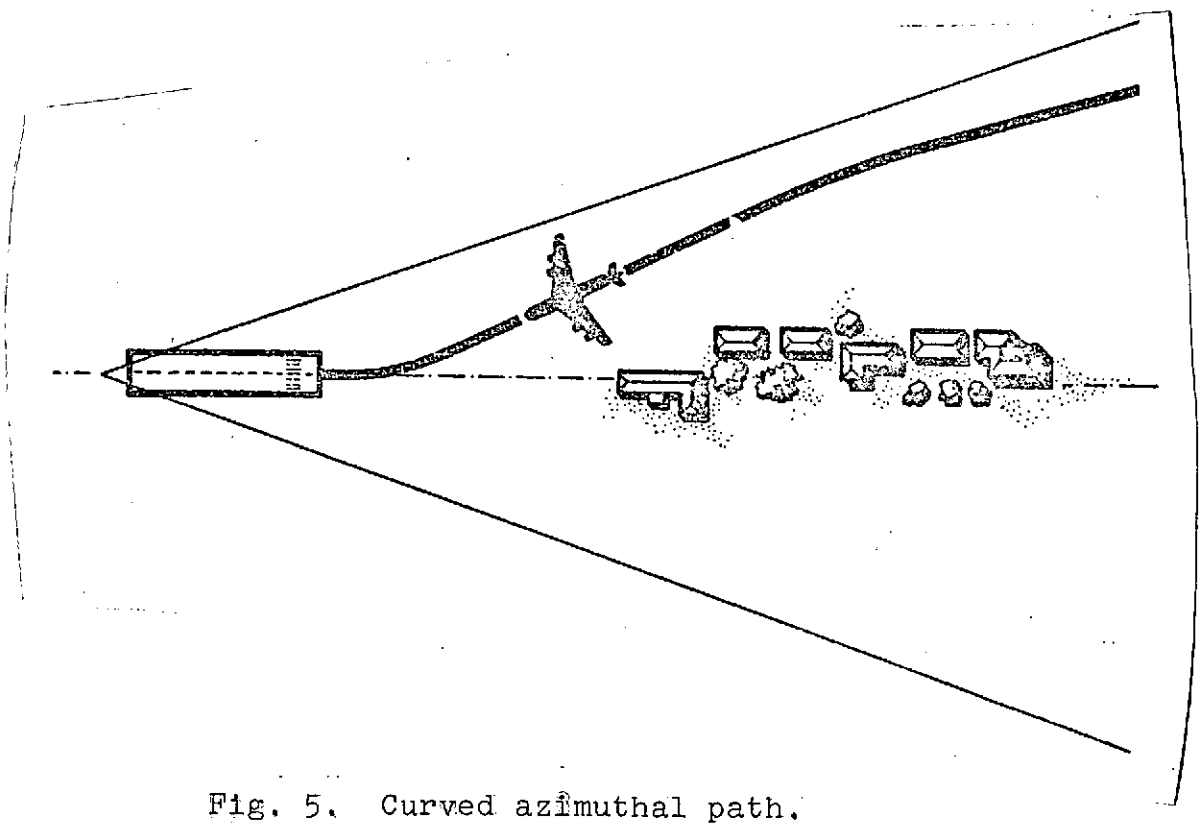

Fig. 5. Curved azimuthal path.

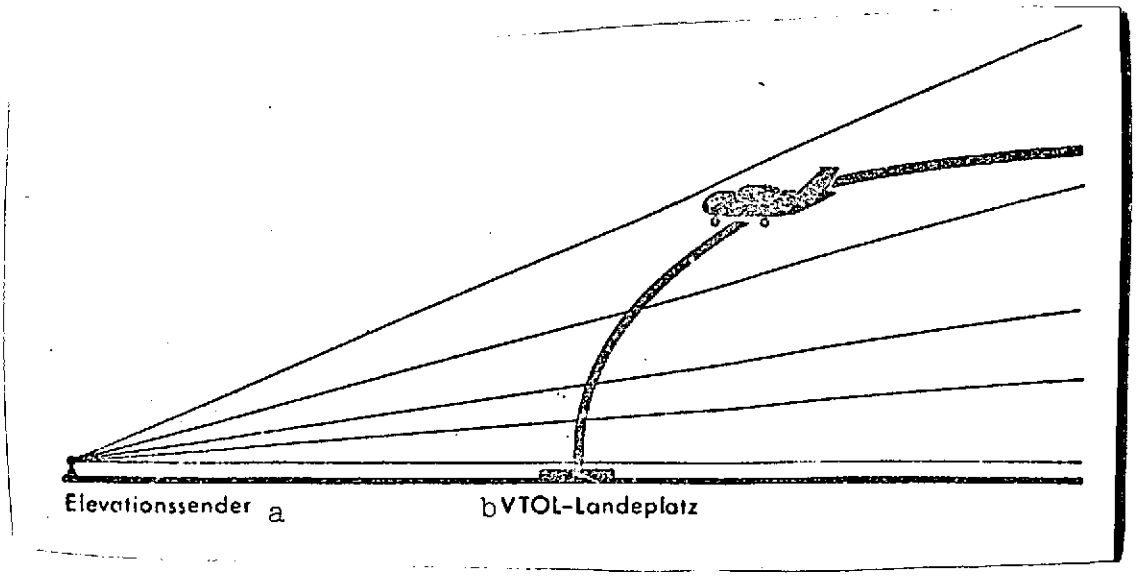

Fig. 6. VTOL approach

Key: a. Elevation beacon
b. VTOL landing pad

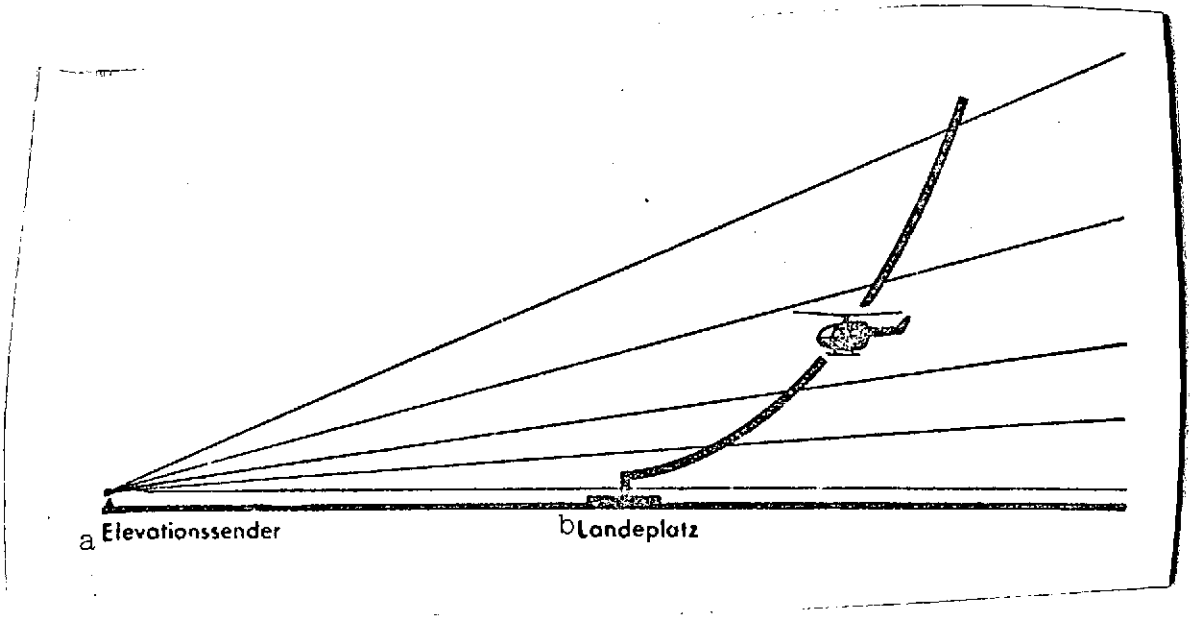

Fig. 7. Steep helicopter approach

Key: a. Elevation beacon
b. Landing pad

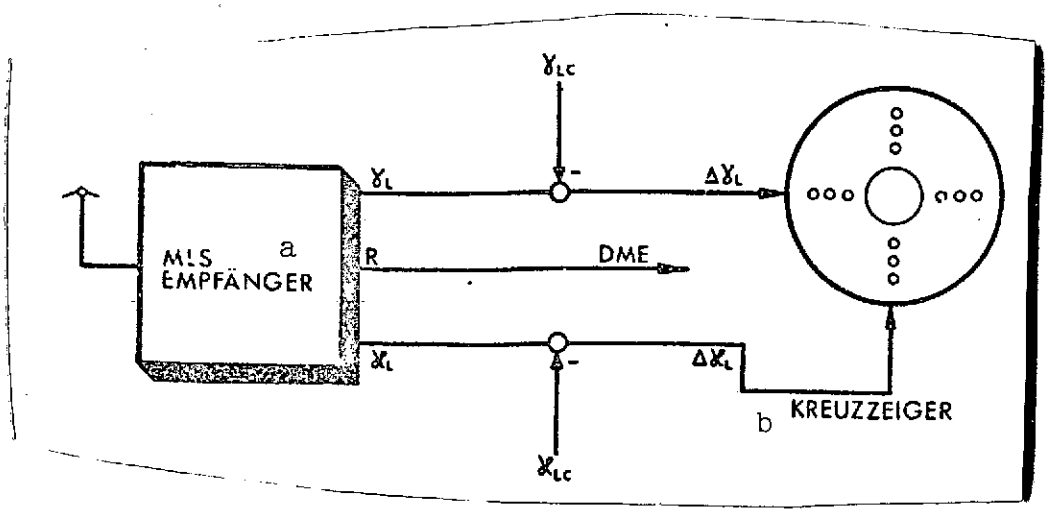

Fig. 8. Conventional indication.

Key: a. Receiver
b. Cross-pointer

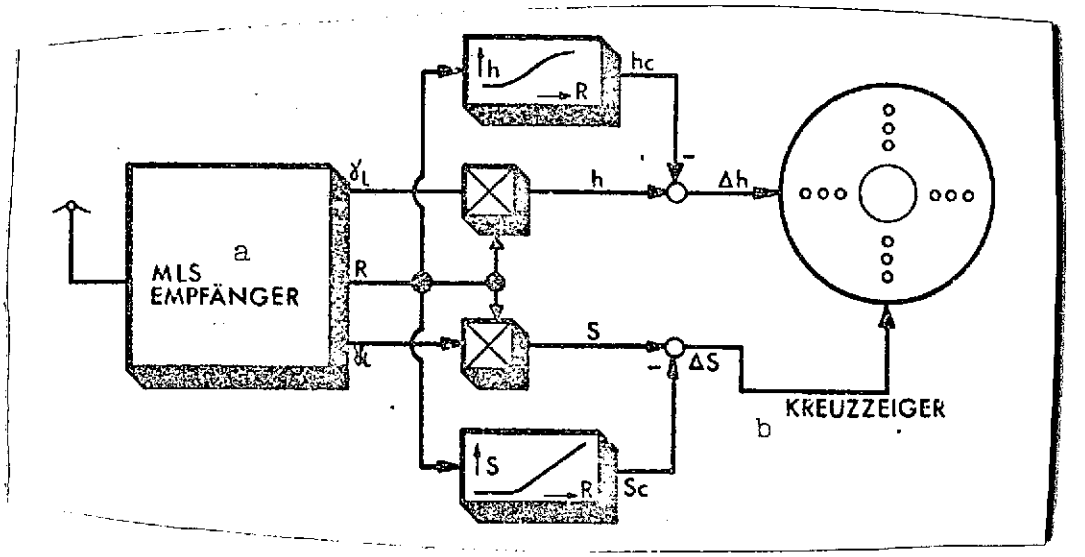

Fig. 9. Production of curved flightpath profiles.

Key: a. Receiver
b. Cross-pointer

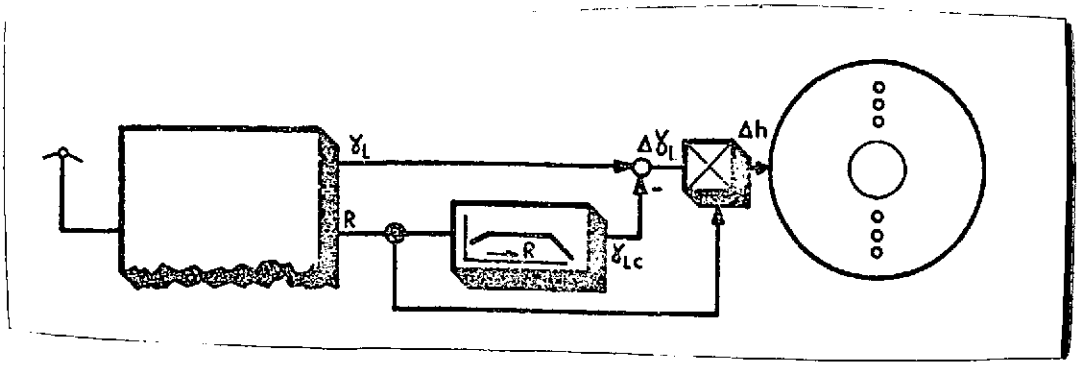

Fig. 10. Production of curved flight path profiles.

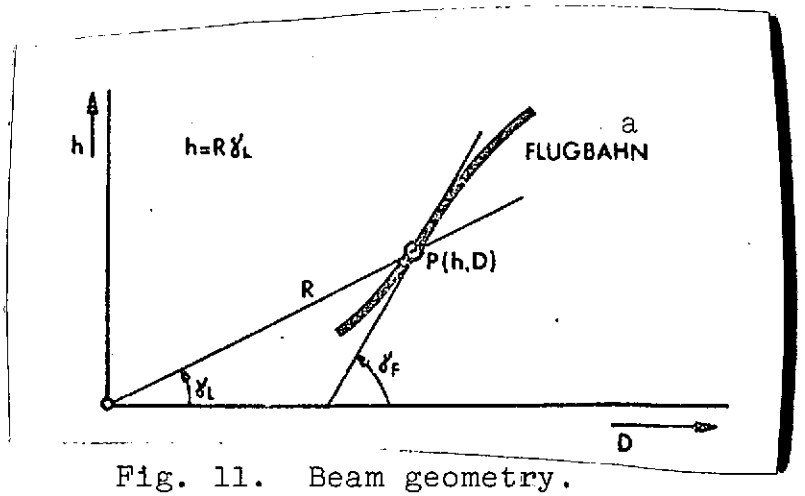

Fig. 11. Beam geometry.

Key: a. Flight path

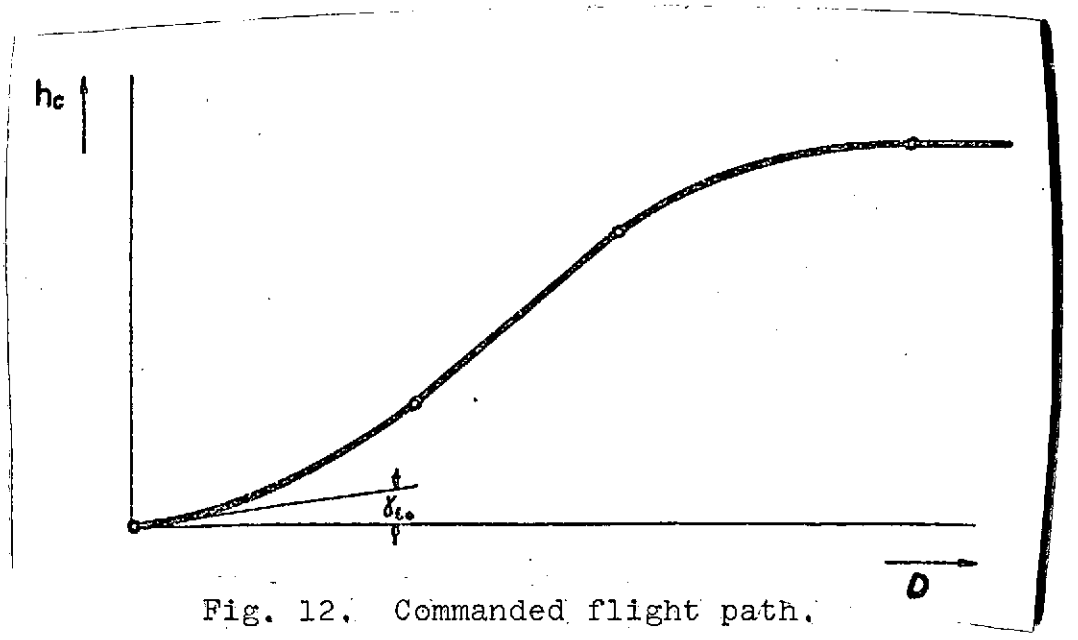

Fig. 12. Commanded flight path.

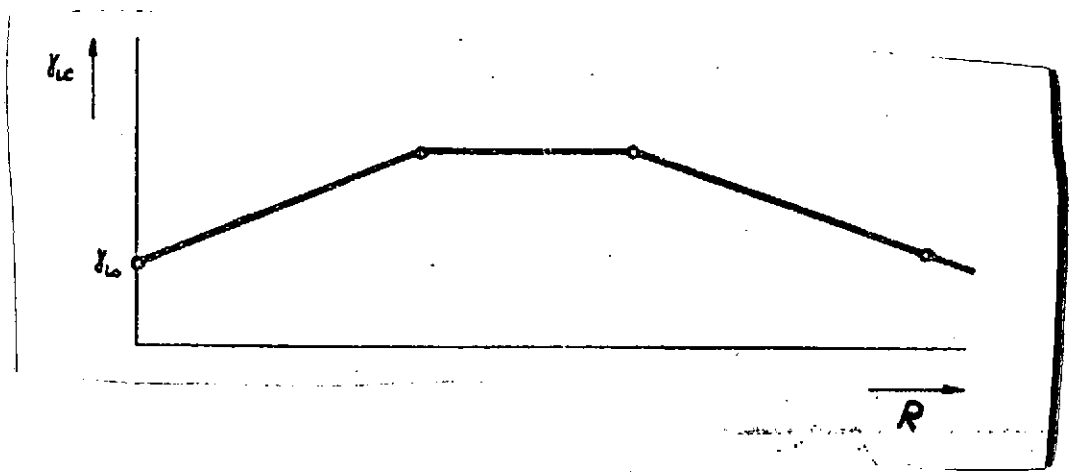

Fig. 13. Commanded flight path angle.

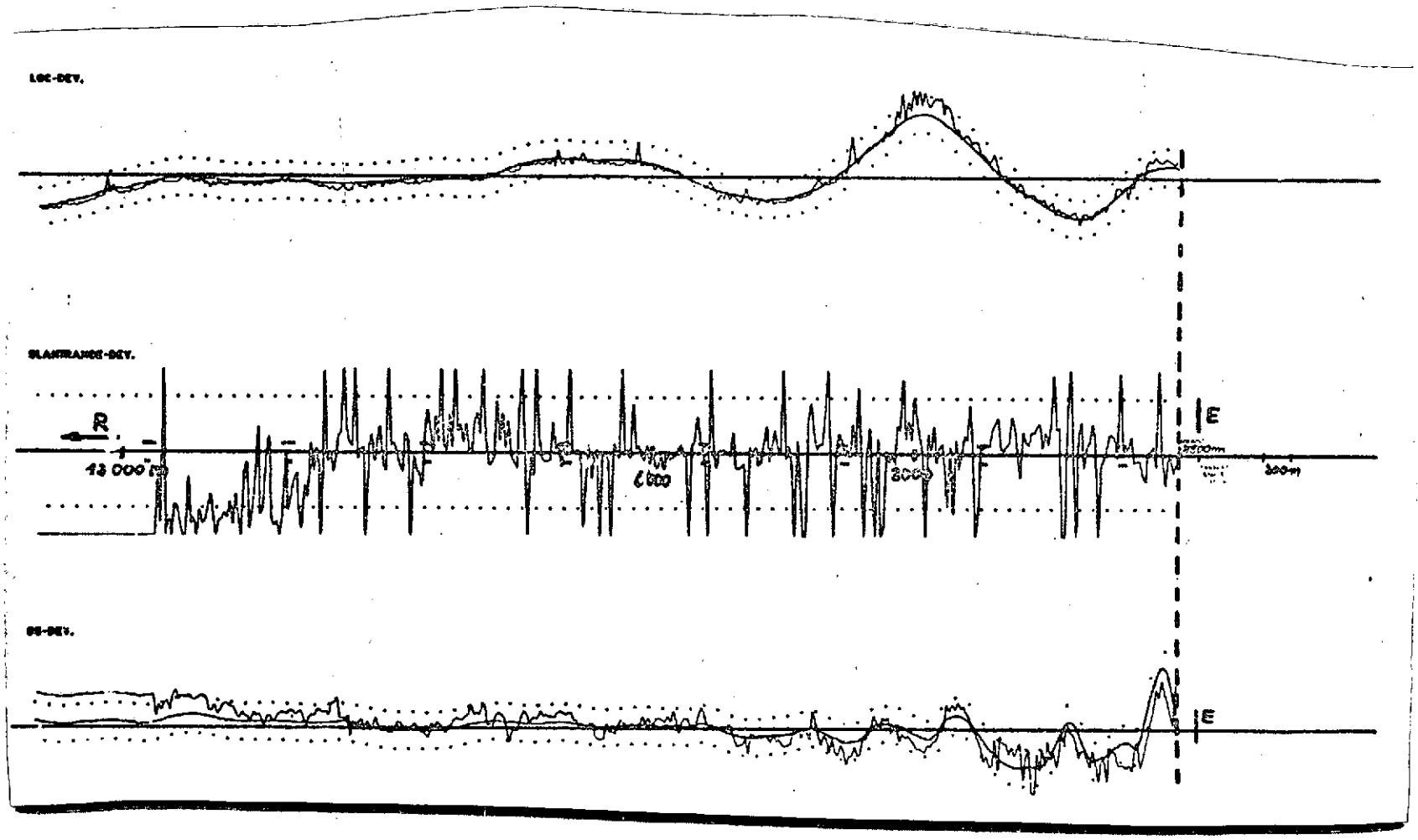

Fig. 14. Stability of beacon guidance in manual approach.

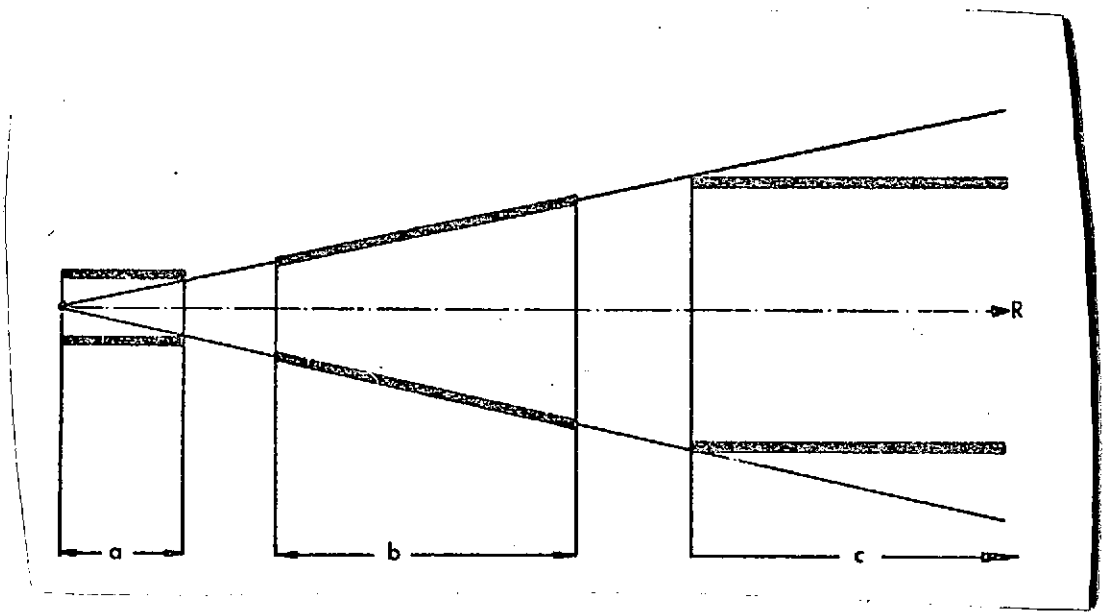

Fig. 15. Ideal lines of constant cross-pointer deflection.

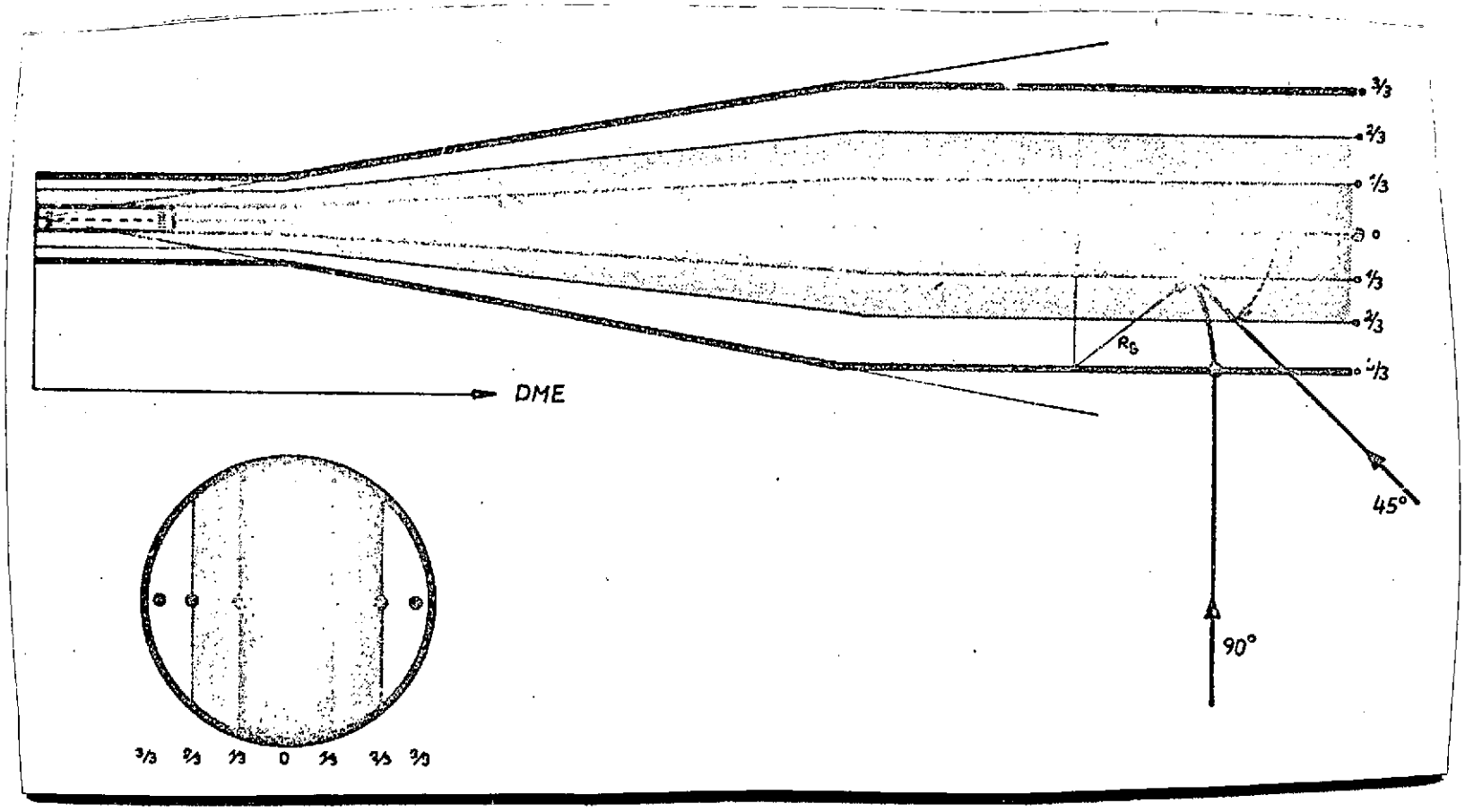

Fig. 16. Ideal lines of constant cross-pointer deflection with bottle-shaped characteristic for azimuth control.

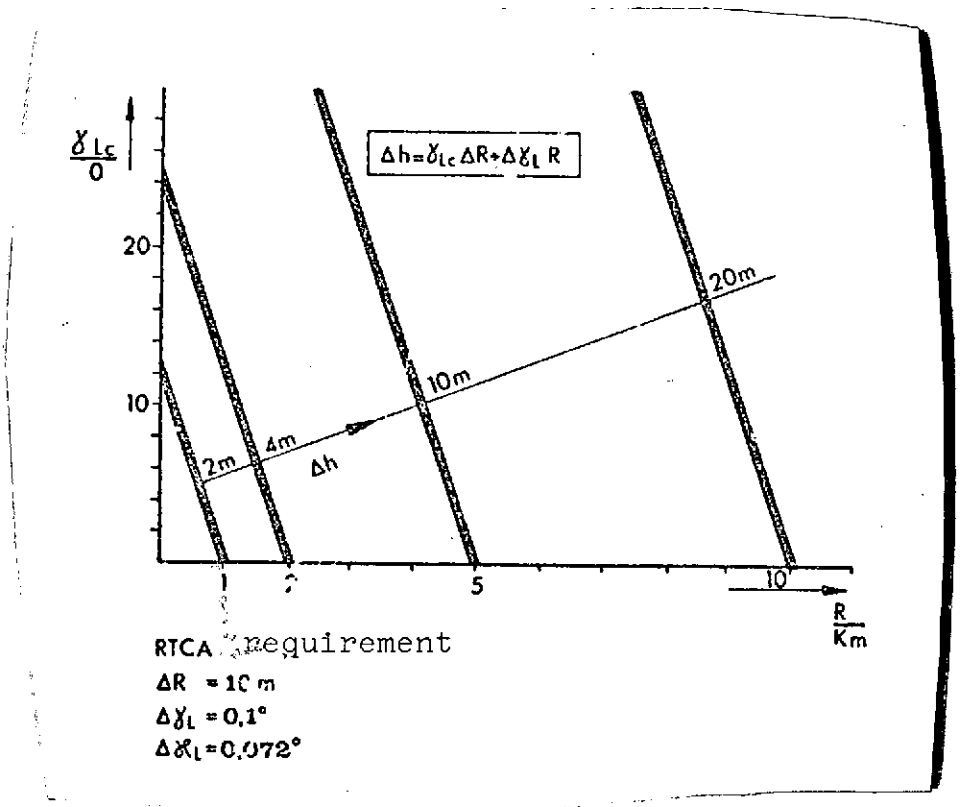

Fig. 17. Lines of constant flight path error.

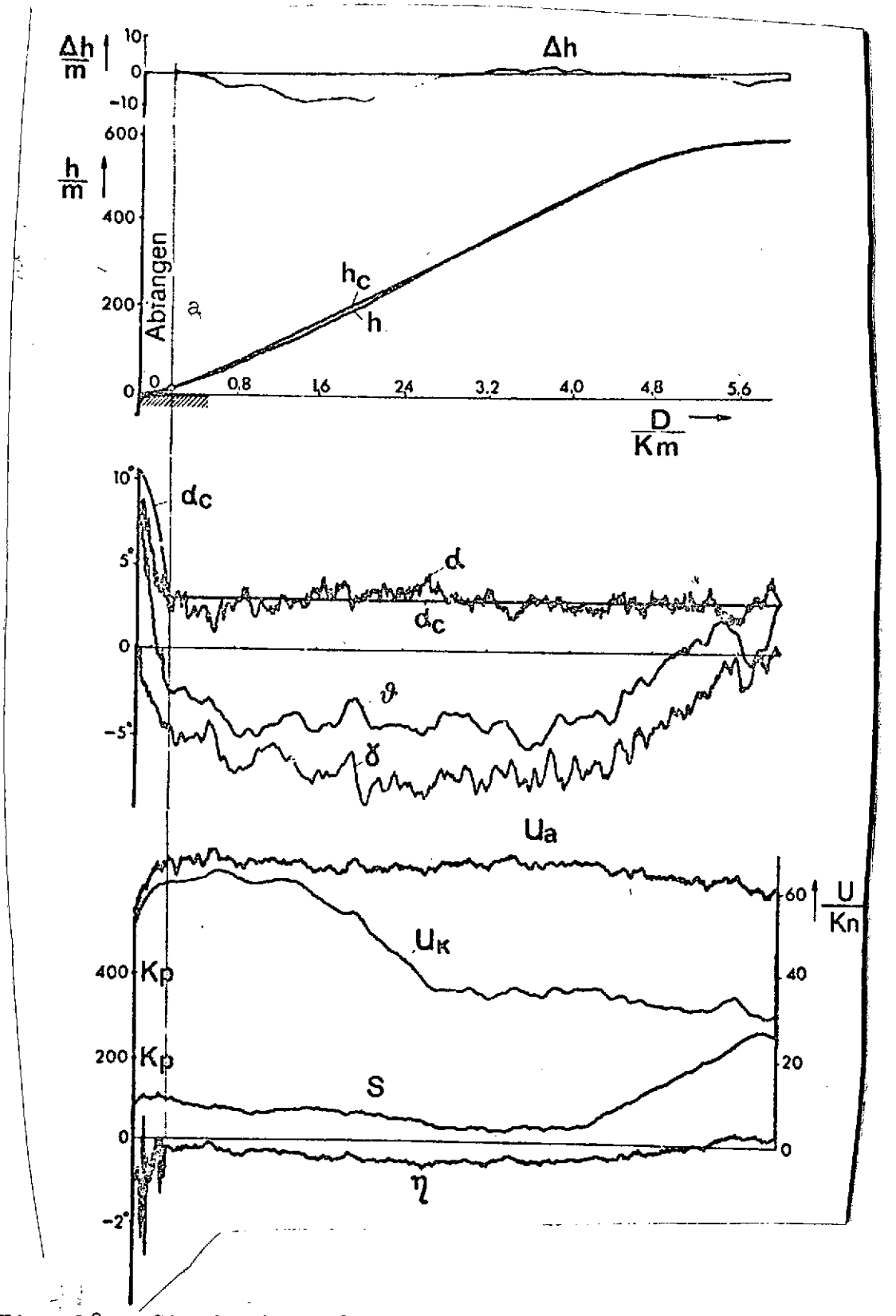

Fig. 18. Simulation of a curved steep approach (Skyservant with FRG 70).

Key: a. Flareout

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